Limits on observations and horizons

1 Introduction

By studying the larger issues in cosmology, such as the understanding of the large scale structures of the Universe, the finite speed of light and the limits of horizons, questions about the physical origins of the Universe, the matter/antimatter asymmetry, problems concerning deep connections (the arrow of time, the constants of nature), we are constantly reminded of the limitations imposed on the scientific method. We will consider these limits because it highlights the achievements of scientists and the limits they constantly come up against in their efforts to understand the material Universe.

2.1 Limits in observations and horizons

There are fundamental limitations on what we can see and how far back (back in time) we can observe the visible matter and its distribution in the Universe. The distribution of matter is important because it helps us to determine the geometry of the Universe. Some objects are so far away that they are very faint and difficult to observe. When we observe objects very far away, we see them as they were billions of years ago and by the time we observe them they may no longer exist.

We observe distant matter by means of radiation or particles it emits travelling towards us and we therefore receive all our information from photons or light covering the complete spectrum of electromagnetic radiation. The finite speed of light limits the region of the Universe we can see. Information we receive travels at the speed of light and any region of the Universe so faraway that light could not have reached us, cannot be observed. At further and further distances we are looking further and further back in time. This makes it difficult to observe the evolution of the object and to separate the evolution of the geometry of the Universe from that of the object.

2.2 Observable Universe

Light only travelled a finite distance since the origin of the Universe. Particles that have travelled since the origin of the Universe must correspond to the age of the Universe. It is impossible to observe anything beyond this limit called the particle horizon. In the expanding

Universe, we call the horizon separating those particles (to become galaxies later) that we can see from those we cannot, the *particle horizon*. In reality we cannot even see as far as the particle horizon, because the Universe was opaque until about 300 000 years after its origin, at the time of recombination. This horizon is called the *visual horizon*.

This means that we can only see as far back as the visual horizon which lies within the particle horizon. It is hoped that in the future we will be able to detect particles beyond the visual horizon up to the particle horizon by means of neutrino or gravitational wave telescopes. Currently they do not have the sensitivity to tell us anything useful.

As a result of these limitations we cannot really say anything about the galaxies or structures that may lie beyond our observation limits. Any statement about structures not within our horizons of observation can strictly speaking not be verified. This means that huge sections of the Universe from which light could not have reached us are beyond our means of detection.

2.3 Universe without a boundary

The exception to the scenarios described above, is universe which is closed in on it self. Then you could travel in one spatial direction and eventually end up where you have started from. This would be the case if the Universe is in the form of a sphere. In such a universe we will see a large number of images of each galaxy in an apparent infinite universe. This is almost like a room of which the walls, floor and ceiling are covered by mirrors and you see a large number of images of yourself fading away in all directions. In such a universe there will be no visual horizon. We would therefore be able to study the geometry of such a universe because we have visual access to all its matter.

The idea of such a closed Universe is an attractive idea. Stephen Hawking described such a universe in imaginary time and studies are underway to find out if we are indeed living in such a universe with no boundary and no beginning, a universe that just is.

2.4 Consequences of observational limits

The consequences of the limitations on our observations of the Universe are that we cannot really say anything about the regions of the Universe that lie beyond the particle horizon. Any such statement is strictly unverifiable.

3 Testing the nature of the fundamental forces

It is impossible to build a particle collider to create energies similar to those that existed in the early and very early Universe. We cannot test the behaviour of matter under such extreme conditions and our theories of these times can therefore not be experimentally verified. The laws of physics that governed these events may or may not be testable in a laboratory. It is said that the inflationary theory solved many of the problems inherent in the Big Bang theory. However, so far we have been unable to detect in experiments here on Earth the field responsible for inflation and the correctness or not of the proposal cannot be verified. We cannot test the proposals for the synthesis of quarks into protons and neutrons and we cannot measure the rate of decay of a proton; we do not know which of the more complex possibilities may be correct.

The early Universe is indeed the only place where some of the laws of physics come fully into play. The collapse of matter in a black hole may be the only other place, but it is inaccessible to observation. We can therefore not test the laws of physics in the early Universe, but have to regard the early Universe as the only laboratory where those laws can be tested. This has led to an important discovery; the comparison of element abundance observations with studies of the early Universe proved that neutrino types are limited to three, not four. This result has subsequently been confirmed by results from the CERN accelerator.

This type of reasoning only works when there are a few clear-cut alternatives that make clear observational predictions and further depends on the assumption of certain cosmological conditions being correct. However, when we consider the really fundamental questions, then even the broad kind of approach we have to take is not clear. Example is the theory that, at fundamental level the four fundamental forces, gravity, the electromagnetic force and the weak and the strong forces were one super force in the very early Universe. Attempts are being made to unify the gravitational force as described in general relativity with the quantum theory, but we cannot use these broad class of theories to determine a unique history for the very early history of the Universe.

The practical limitations in testing the laws of physics are therefore major limitations in determining what really happened the very early times. Energies attainable in colliders will always be limited by practical considerations, but events in the early Universe can attain unlimited high energies.

4 Physical origins

The above problems also apply when we consider the origin of the Universe, which set the conditions determining what exists today. The Big Bang theory implies that there must have been a moment of birth of the Universe when conditions were so extreme that the laws of physics broke down. The birth of the Universe also implies that the laws of physics did not exist before that point.

Various theories have been proposed to describe the very early Universe. Despite this uncertainty specifically about the nature of a theory of quantum gravity, we can claim that the underlying wave-like nature of matter, must apply here also. This enables us to make quantum cosmology models claiming to correctly represent the results of the as yet unknown theory of quantum gravity when applied to the early Universe.

5 The no-boundary proposal

I have briefly referred to Prof. Stephen Hawking and Jim Hartle's proposal for a Universe in imaginary time with no boundary. It is much like the Earth. You can travel around the Earth and you won't fall off its edge because it has no boundary. In such a universe could be a region where time did not exist; instead of the usual three spatial dimensions and one of time, there were four spatial dimensions. There is no boundary to this Universe and it has no beginning and no infinities such as implied in Einstein's general relativity. Time does have a beginning in a transition from this strange 'Euclidean' state to a normal space-time structure. This has originally been developed as a cosmological idea, but there are classical solutions of Einstein's equations with the same property. A concern about this proposal is the testability of the theory.

Such proposals suppose the unravelling of some of the underlying conundrums of the quantum theory that have not yet been solved in a satisfactory manner. The issues are the role of an observer in the quantum theory, and what causes the collapse of the wave function, an essential feature of measurement in the quantum theory. At the macroscopic level these problems do not arise as significant in laboratory tests, but they are important if we apply the quantum theory to the whole of the Universe.

The Wheeler-de Wit equation underlying quantum cosmology cannot be tested in its own right despite its basis established in physical laws. Underlying concepts, such as the wave function of the Universe have a questionable basis in this context because they are associated with a probabilistic interpretation and make no sense when applied to a unique object such as the Universe.

6 Initial conditions

If we are to describe conditions in the early Universe by applying physical laws and make predictions of what the current epoch of the Universe should look like, we come up against the requirement to specify the initial conditions or boundary conditions. We have to accept that the Universe had a beginning and the conditions at the beginning were probably unique, not be repeated anywhere since (or at least, none are accessible to our observations). The notion of a law to describe such a situation faces considerable difficulties. If we apply the "law" once only to a unique situation, the distinction between a physical law and the initial conditions makes no sense. Furthermore, that law cannot be subject to empirical test in the same way as other physical laws.

Whatever law we may use to describe the situation we can only do one test, see if its predictions describe the Universe we see. Even then such a law may not be unique. There may be several other laws or underlying approaches that give the same result and they cannot be distinguished from each other on the basis of experimental tests. The Hawking/Hartle proposal for a "no-boundary" universe can only be "tested" on the basis whether it conforms to the criteria for good theories.

The Universe we observe is the remnant of the initial state, after it has been processed by processes in the early Universe and then in stars. But this understanding of initial conditions does not answer the ultimate issues of origin and existence, such as *why the initial conditions had the form they did*.

7 Deep connections

In developing questions, it is important to understand the *interconnectedness of the Universe*. The choice of questions determine the initial nature of matter, the space-time geometry and the choice of initial conditions of the Universe profoundly affects the nature of physics in other ways. We consider three examples, namely Olber's Paradox, Mach's Principle and The Arrow of Time.

7.1 Olber's Paradox

A classic illustration of the interconnectedness of the Universe is known as Olber's paradox and asks the question: why is the sky dark at night?

The point is if we consider a simple static Universe uniformly filled with shining stars, the radiation received per star goes down with the inverse square of the distance from the observe, while the number of stars goes up with the square of the distance. Add up the effect of all the stars, the two factors in the square of distance cancel, and we conclude that the radiation we observe becomes infinitely large as we consider the combined effects of more and more distant stars. According to this model the night sky should be infinitely bright. In fact, according to this the sky (night and day) should in every direction be as bright as the surface of the Sun.

We may conclude that such a bright sky at night will be uncomfortable, but nothing could be further from the truth. If this were the case, the Earth could not get rid of its waste energy by radiating it out into space, since space would be everywhere as hot as the surface of the Sun; the Earth would heat up until it was in equilibrium with the temperature of space. In short, life cannot exist on Earth which will be molten rock and any organic molecules would be disintegrated by the radiation.

What is the solution? This scenario ignored three factors namely, the expansion of the Universe result in received light from distant galaxies to be red shifted, causing a decrease in the intensity of light received, greatly reducing the expected radiation from distant stars. Secondly, stars have a limited amount of nuclear fuel and do not shine forever but die; the assumption that stars shine forever is false. This model ignores a very important law; the conservation of energy.

In the third place, the Universe itself has a finite age. If we look back far enough into the past we will observe an era when stars have not yet been turned on; matter at that time is dark because stars have not yet formed and the pre-existing background radiation is nothing other than the cosmic microwave background radiation which we observe as being at 3 degrees Kelvin. The essential point of all three factors is that the Universe is not in a state of equilibrium, as this model supposed.

Thus this model ignores the simple fact of the expanding Universe and it shows how we cannot ignore the effect of distant matter simply because it is so far away from us. There is so much of it, that its effects could be very important in daily life.

7.2 Mach’s Principle

Another example of this type concerns the origin of inertia (property of an object that resists its being accelerated). A simple fact that has puzzled scientists for nearly 300 years is that the very distant galaxies stay in fixed positions in the sky, when compared with a non-rotating local reference frame, as defined by local dynamical experiments. In other words, while stars appear to move across the sky relative to the (rotating) Earth, they appeared fixed relative to the plane defined by rapidly rotating gyroscopes as used for the inertial guidance of submarines and aircraft.

Inertia is a property whereby a freely moving body continues in a straight line relative to a non-rotating reference frame, but it moves on a curved path relative to a rotating reference frame (due to “inertial forces” such as the centrifugal force that pushes you towards the side of the car as it goes around a corner).

This is in accordance with General Relativity according to which gravity (as a long-range force) and inertia are closely related. Now Mach’s idea is that *local inertia properties are determined by distant matter*; as in the case of the Olber’s paradox, a single star contributes very little but the total contribution of all the stars when one adds the contribution of every star, is very large. The choice of the local inertial rest frame and the rest frame of distant stars is not a coincidence; it is because local inertia – underlying all local dynamics – is *caused* by distant stars.

Einstein tried his best to develop his static Universe model so that it would show that General Relativity fully incorporates Mach’s principle in its structure. However, the de Sitter Universe model developed at the same time showed this not to be the case. How are we to interpret this? Suppose there was only one galaxy in the whole Universe, not the billions that we can see, then the inertia of say one kilogram of matter would be far less than we now measure it to be. Therefore if we could slowly remove galaxies from the Universe, the inertia of matter would gradually decrease.

The issue remains unresolved. Of course we could argue that as the Universe expands the force of gravity gets weaker, resulting in a decreased gravitational effect. But this has not been confirmed either. If it occurs it is too weak to detect. But the important point made is that is quite possible that if the structure of the Universe were totally different, the laws of physics we experience may be quite different too.

7.3 The Arrow of Time

One of the most vexing problems in physics is the arrow of time. The problem is that we all agree that times passes but, *the fundamental laws of physics is time symmetric;* they run equally well forwards or backwards in time. Therefore the undeniable arrow of time is problematic. We can argue why it exists (a broken glass won't reassemble itself into an unbroken glass), the problem is that these arguments work both ways; they can be used to explain the arrow of time, but cannot tell which direction of time is future and which is the past.

The problem is further compounded by the fact that there are several apparently independent arrows of time (quantum mechanics, thermodynamics, electrodynamics and evolutionary biology). There are two suggestions to answer this conundrum. On the one hand the arrow of time may be related to the expanding Universe. On the other hand the arrow of time may be determined by specific boundary conditions for local physical laws at the beginning and the end of the Universe. Note that we cannot say that the boundary conditions at the beginning of the Universe would establish this one-way flow, because until that flow is established, the beginning and end of the Universe is on equal footing; there is no intrinsic distinction between them.

It is very important to note how initial conditions for some physical field are correlated with each other at the beginning and end of the Universe. In the past they should be uncorrelated, but in the future they should be correlated. For instance, after a glass has fallen to the ground and broken, the pieces disperse away from where it has fallen. We cannot simply reverse the velocities of the fragments to re-assemble the glass. The correlations required are too exact. It requires an incredible degree of coordination to achieve this.

Whatever the solution, it is clear that according to our present understanding of the nature of physics, the arrow of time is not embedded in the fundamental laws; rather it is a result of the boundary conditions for physical quantities imposed at the beginning of time (and probably also at the end of time). Whatever theories we may have about this, fact is that this cannot be tested by any physical experiment.

7.4 The unity of the Universe

The examples given above point to deep connections and unity of the physical Universe, not only in the effect of microscopic laws on the macroscopic structures as envisaged in the inflationary picture of the Universe, but also in terms of the nature and functioning of those laws. In fact the examples given above show that there may be no clear cut distinction between *boundary conditions for physical laws* at the beginning of the Universe, and the *nature of local physical laws* as the boundary conditions for those laws at the beginning of time are part of the structure of the Universe and cannot be changed; they are the essential feature characterising the physical laws themselves. From the viewpoint of an ensemble of universes it is just one of a whole set of possible boundary conditions, yet this may critically affect the nature of local physics within a specific Universe so that they are experienced as absolute and immutable. In a cosmological sense the distinction between initial conditions and physical laws may become blurred; that is these features may become highly interdependent.

8 The Uniqueness of the Universe

What we come up against time and again is the uniqueness of the Universe, and the problems as we try to unravel this uniqueness.

Cosmology is the ultimate historical science, because there is only one Universe. In other historical sciences there are other similarities to compare a particular object with (in geology there are mountains and continents; in astronomy there are stars, galaxies and planets).

The uniqueness of the Universe is the central problem in cosmology. There is nothing whatever we can compare with the study of cosmology both in practice and in principle.

That is the reason why our theories about the Universe cannot be subject to confirmation in the normal sense; our choice of the physical laws that govern the Universe and of the particular initial conditions occurred in a unique Universe. Some scientists propose the existence of a multiverse, a family of universes, making our Universe no longer unique. This merely postpones the essential problem, because it is then the multiverse that is unique. The problem recurs.

In cosmology we can only observe what is there, and compare with predictions and theories. In this way we can learn a lot about the physical nature of the Universe and the way it functions. However, we run into problems when we try to answer the questions referred to elsewhere in this article, in particular when we refer to the initial conditions.

9 Uncertainty at the Foundations

So far we had a very gloomy picture of cosmology and fundamental physics. Unfortunately the picture is not yet complete. We must note that *certainty is not even attainable in the logical sciences.*

The mathematician, Kurt Gödel showed that even mathematics as a science cannot be showed to be consistent. Furthermore the concepts underlying the probability theory, which is required to test any physical theory on the basis of real (noisy) data, are also on shaky ground, since the concept of a random number is difficult to pin down.

We therefore have to conclude that *certainty is unattainable at the foundations of understanding in all areas of life,* including fundamental physics and cosmology and even mathematics. This is to say that what we can learn with reasonable confidence *about foundational issues* is strictlt bounded. A mature attitude in cosmology must take into account uncertainty and make it an acknowledged feature of the way we approach understanding the Universe. Once we have accepted these limitations, giving up the unattainable hope of certainty, we can attain satisfying and even profound understandings of the Universe and the way it works.

NOTE

I would like to express my thanks to Professor G.R. Ellis of the University of Cape Town, who provided me with information on the Causal Structure of Space-time at the Quantum Level, from which I was able to compile this article.

Frikkie de Bruyn
Director: Cosmology Section of the Astronomical Society of Southern Africa